Ronald Hudson

HIGHWAY RESEARCH RECORD

Number 338

Research Project Design and Program Development

6 Reports

HIGHWAY RESEARCH BOARD

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HIGHWAY RESEARCH BOARD

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Part 1

Foreword

The first 5 papers in this RECORD on the guidelines for research design have been developed from a conference session at the 49th Annual Meeting chaired by George W. McAlpin. The general objective of the session and the papers was to bring out the analytical aspects of research design, with particular emphasis on experimental design and the application of statistical methods to controlled experiments and surveys. Irick presents the framework of the conference and identifies and discusses 5 research design steps: systems analysis, information analysis, program formulation, project scheduling, and experiment design. Anderson addresses himself to the design of experiments, outlining the fundamentals of statistically designed experiments and illustrating their application to a specific example. Hudson describes the applications of the principles to laboratory research projects, giving some examples and creating an interesting myth. Beaton identifies the basic categories of field experiments and discusses the application of design principles in this area. In the fifth paper, Finkner explores the use of statistics in planning sample surveys.

Contents

Research Design

PAUL IRICK, Highway Research Board

•IN MY BRIEF REMARKS I shall give a general background for the main subject, experimental design. In essence, I shall try to present a framework for the major aspects of research design of which experimental design is a very important part.

CONCEPT OF RESEARCH DESIGN

I will start with the notion that research is the study of systems for the purpose of producing information about that system. Of particular corcern is the study of transportation systems, transportation subsystems, or systems closely related to the transportation field. I think that the main product of research is information that is useful for the operation, management, or further study of such systems.

To increase the likelihood that useful information will, in fact, result from research activities, we believe that research must be designed; that is, a rather complete set of plans needs to be developed for the research. To this end, we have identified 5 research design steps (Fig. 1): systems analysis, information analysis, program formulation, project scheduling, and experimental design.

I shall briefly discuss the first 4 of these steps. The other papers will be largely devoted to the fifth step. Because these research design steps are interrelated and highly interactive, it is important that those having responsibility for any one step be closely involved with all the other steps.

SYSTEMS ANALYSIS

We believe that research design should begin with a suitable analysis of the system that is to be studied (Fig. 2). A system is comprised of activities, inputs, outputs, utilities for conducting the activities, environments within which the activities occur, and characteristics of activities, inputs, outputs, utilities, environments, the system at large, and the related systems. A system analysis will generally include both the identification of all these system aspects and their interrelatedness.

We would also ask that the system analysis name variables and attributes that may be used to describe the system. We may suppose that the system's independent variables are those that describe system activities and elements and that system characteristics may be identified with dependent variables.

A minimal result of systems analysis is an explicit or implied list of the types of information that are necessary and sufficient for understanding and improving the system under study.

INFORMATION ANALYSIS

Although the systems analysis should indicate information needs, it does not necessarily bring out the extent to which the needs have already been met.

We believe the second step in research design should be an information analysis that reveals the existence and adequacy of available information on the system under study (Fig. 3). The acquired information can then be evaluated and analyzed with respect to information needs. The analysis should reveal information gaps and inadequacies, particularly from the statistical point of view. We suppose that the net result is a clear picture, perhaps in terms of problem statements, of information needs that might be satisfied through research activities. Thus we consider research needs to be equivalent to needed information on the system under study.

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In passing, we observe that information analysis is frequently bypassed until the completion of program formulation and project scheduling steps—or even until the com pletion of the experimental designs. Thus we may find that literature searches may not be made until project investigators begin their work. Unfortunately, this practice sometimes brings out too late that the research design can only produce unnecessary or inadequate information.

PROGRAM FORMULATION

The third step in research design is to formulate one or more research programs whose goals cover at least part of the information needs. In this discussion we will suppose that program formulation is the structuring of research activities into programs and projects within programs, and that program formulation includes the statement of program goals and project objectives (Fig. 4). Finally, we consider that

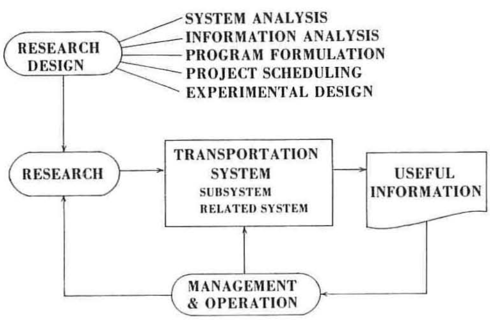


Figure 1. Research concepts.

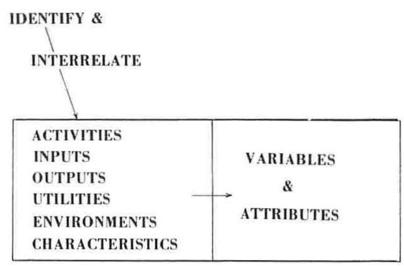


Figure 2. System analysis.

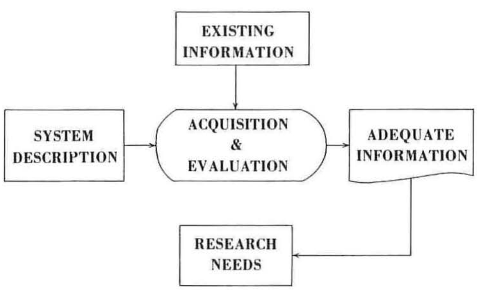


Figure 3. Information analysis.

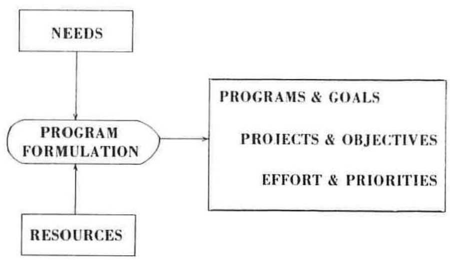


Figure 4. Program formulation.

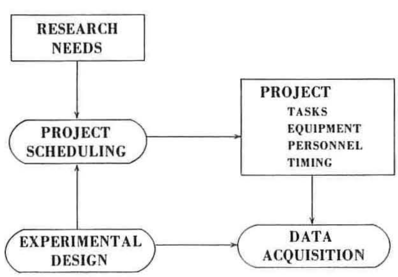


Figure 5. Project scheduling.

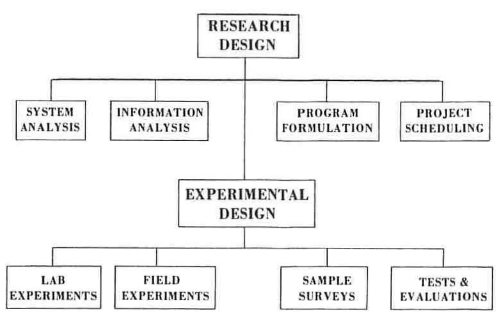


Figure 6. Research and experimental design.

program formulation should include levels of effort and priorities for program and projects.

PROJECT SCHEDULING

Our fourth step for research design is project scheduling that identifies project tasks and personnel, equipment, and timing considerations for the conduct of project tasks (Fig. 5). Project scheduling thus provides management information for research administrators and constraints for the experimental designs that will be used to acquire the information.

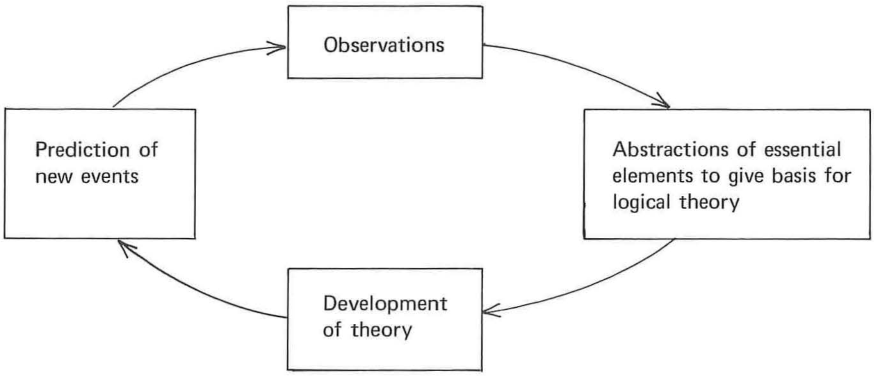
SUMMARY

In summary, we have supposed that research design involves 4 steps that need to be accomplished in one degree or another before definitive experimental designs are developed for the acquisition of research information (Fig. 6): system analysis, information analysis, program formulation, and project scheduling. We hasten to repeat, however, that these steps are not independent of one another and their development should proceed in full consonance with the development of experimental designs.

Design of Experiments

VIRGIL L. ANDERSON, Purdue University

•RESEARCH DESIGN may be considered closely allied to the scientific method. Kempthorne (1) describes the scientific method in a circular notion as follows:



The uses of statistics comes in the observations by designed experiments and analysis of data from the experiments. The design should never be considered before the analysis is contemplated.

FUNDAMENTALS OF STATISTICALLY DESIGNED EXPERIMENTS

Ingredients for Well-Designed Experiments

The first of these ingredients is to have a well-defined problem. This may take many hours, but in general an hour spent here usually saves at least ten later. In general researchers should not run one-factor-at-a-time experiments, and complete factorials are too expensive. Hence fractional factorials and modifications must be considered.

Another ingredient is to have enough replications to show "practical" significance. The notion of practical significance must be associated with cost. There is no reason to run an experiment to show statistical significance (in a probability sense) when the difference of the means is so small that it does not pay the engineer to make a change in practices. This concept can be incorporated in the experiment at the design stage if discussed thoroughly.

Two additional ingredients are to outline the analysis of the data at the design stage and to design the experiment as economically as possible.

Basic Requirements for Designs

In the past, the 2 requirements given were randomization to allow for unbiased estimates of the parameters of interest and replication to allow for an estimate of the

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experimental error. Somehow, the engineers who have worked with me recently seem to know these, but 2 requirements are not understood.

Inference Space—The concept is the same as that of the statistician's old word "population", but engineers appreciate inference space better because it implies how far they can apply the results or what inferences they can make from the data taken from the designed experiment.

Restrictions on Randomization—In general, research workers in all fields in which I have consulted have difficulty understanding that, when a restriction on randomization is placed on the data-taking mechanism, this peculiarity must be accounted for in the analysis. It has been my experience over the past 10 years or more that almost no truly factorial experiments are run; they almost all have a tinge of "split plot" in them. I do not expect you to understand this completely here, but I will try to demonstrate it later. When canned factorial computer programs are run on your data, you will more likely misunderstand the results for your experiment than understand them if you do not understand restrictions on randomization.

Methods of Handling Extraneous Variables

Rigid Control—The inference space may be too narrow for you, but for some experiments this is desired.

Classification—This includes the treatments or factors, the blocks or restrictions on randomization, and anything else that has to do with controlling the levels of the variables to be included in the experiment.

Concomitant Information—Measuring another variable at the same time as the one of interest allows additional information with few observations.

Randomization—After rigid control, classification, and concomitant information have been used to control or measure extraneous variables to obtain unbiased estimates, randomization is used to scatter the influences of those extraneous variables missed by the first three.

Prior Information

Some statisticians do not like to use information from prior investigations, especially if randomization has been neglected. There are occasions in engineering problems, however, when prior information is necessary before an experiment can be run intelligently. If care is taken, I believe historical data can be utilized.

AN EXAMPLE

Consider the problem of deciding on the best prosthetic cardiac valve to choose from 4 types at 6 different pulse rates. An apparatus constructed by an engineer used water in the mechanical device for blood, a pump for the heart, and a certain type of tubing for blood vessels. The valves could be installed and replaced in the system with some difficulty. The pulse rates could be simulated by varying the speed of the pump quite easily.

Complete Factorial

If all 24 combinations of the valve types by pulse rates could be repeated 2 times, there would be 24 times 3 or 72 treatment combinations to run. If all of these 72 were run completely at random, as is assumed in a complete factorial, the engineer would have to disassemble his machine 71 times. The linear model to use for the analysis could be

$$Y = \mu + V + P + VP + \epsilon$$

where

Y = the variable to analyze such as back pressure or a flow variable,
μ = the overall mean,
V = the effect of the valve type,

P = the effect of the pulse rate,
VP = the interaction, and
ϵ = the error for testing the effects of V, P, and VP.

The amount of information available to investigate the valve types is associated with ϵ, which has 48 degrees of freedom. In this case the canned factorial computer program is appropriate.

Split Plot Design

Almost no engineer would take the time to disassemble the apparatus 71 times for such an experiment. He may be willing to put a valve type in the apparatus and run all 6 pulse rates at random. Then he may remove that valve type and put another one in at random. Then he may remove that valve type and put another one in at random and run all 6 pulse rates at random. He may do this for the other 2 valve types and repeat this procedure with different randomizations for 2 more times. In this case he has restricted his randomization by allowing the same valve type to receive all pulse rates before disassembling the machine. Somehow this must be accounted for in the analysis. One linear model that could show this, if certain assumptions are made, is

$$Y = \mu + V + \delta + P + VP + \epsilon'$$

In this case δ has been added in the model to account for the randomization restriction on valve types, and V is tested by δ, which has only 8 degrees of freedom. Also ϵ' has only 40 degrees of freedom, which is not much loss.

The important point to engineers is that, by making the experiment easier to run, the information on valve types, per se, may be reduced and all this must be accounted for in the analysis. In this case the canned factorial computer program is wrong and must be modified for a correct analysis.

SUMMARY

In the example, rigid control was used as much as possible by the engineer, classifications were the valve types and pulse rates, concomitant variables could be the back pressure or a flow variable, and randomization was used.

Most important, however, was that the inference space was the human beings to use these prosthetic heart valves. How immediately applicable the results would be must be ascertained by the engineers, medical doctors, and statisticians. Also, the restrictions on randomization must be accounted for if the second design (a split plot) were used. Care must be given to the analysis of such data.

REFERENCE

1. Kempthorne, O. Design and Analysis of Experiments. John Wiley and Sons, New York, 1952.

Statistical Experiment Design of Laboratory Experiments

W. R. HUDSON, University of Texas

•IN BOTH the university and in the real world one often sees engineers and students, and professors for that matter, working with test data, usually plotting them in an effort to find out what they think the data are telling them. In doing this, we often massage the data in various ways. We may find it desirable to throw out "bad" data points or to bias the curve so that it looks good to us. In doing this we ought to keep in mind 2 things:

1. We can do anything we desire to the data as plotted on that graph and we can do anything we desire with the shape of the curve, and our judgment may make the line better or worse.
2. We are not usually interested in those data or that line because we will never use those data again. They are samples from the real world. What we are really interested in, usually, is what we can expect to happen under similar conditions either in the laboratories or in the outside world. In this case, what we do with the data or with the line makes quite a bit of difference because what the "truth" is or what nature intends to do will not be affected one bit by what we say about the data or the line.

I think this is best illustrated by the following example. I walked into a research laboratory one day and observed a friend of mine carefully plotting 3 points on a graph like that shown in Figure 1. The graph represents the results from a complex test (Test A) compared to the results of a very simple test (Test B) for many pairs of tests. Observe the perfect correlation line that he already had plotted and the large number of points that seem to fit the line very closely. I observed my friend plotting from his data sheets the 3 points shown in Figure 2 by crosses through dots. As I entered the room he seemed to be very disturbed. I said, "Friend, what is the matter?" He said, "Oh heck, I thought I had 3 new points for my test correlation, but as you can see I have only one." With that he erased the 2 external points. There is no question that the set of points does represent a group of soils for which the 2 tests did correlate well. Figure 3, however, shows the set of all correlations run by my friend. He has thrown away all the points not shown on Figures 1 and 2. Unfortunately, he proposes to use the correlation in all circumstances, that is, to substitute Test B for Test A as his specifications test. I think that you can easily see the error in this approach. He threw away the unwanted points, but nature will not throw them away.

There is another area of major concern in our laboratory work at a different level. Many of us do not treat our data as shown in Figure 1. We do, however, divide very complex problems into parts and look at them with a one-factor-at-a-time approach, ignoring the effects of the other variables and the resulting interaction. I would like to illustrate this with a little myth. Now remember that a myth while not literally true represents a truth.

> Once upon a time there were 3 boys. Their names were Ronnie Hudson, Johnny Beaton, and Isaac Newton. Now, Ronnie lived down in Texas where lemons and grapefruit are grown. As he rested under the trees, he noted with his high intelligence that grapefruit falling on his head from the tree hurt much more than lemons. Being very astute and very scientifically minded, he ran several experiments involving objects and the resulting force with which they

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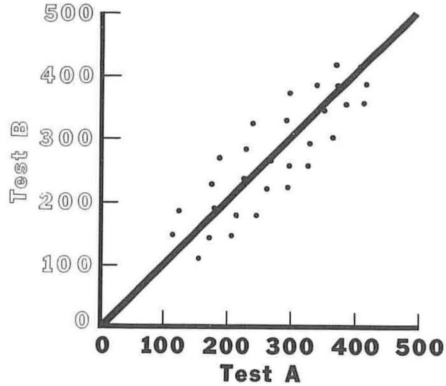

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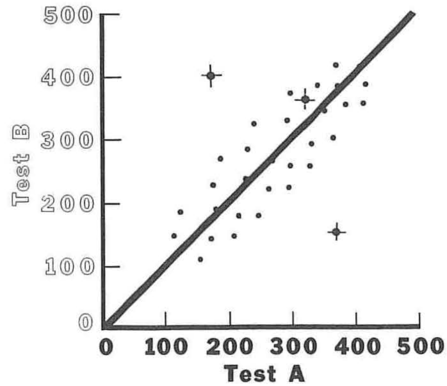

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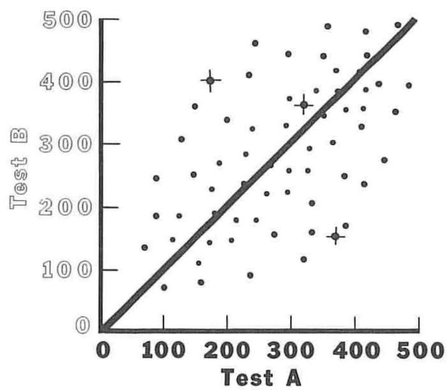

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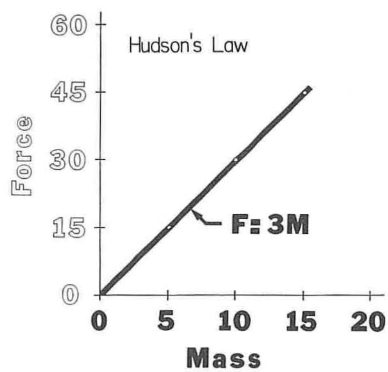


Figure 4.

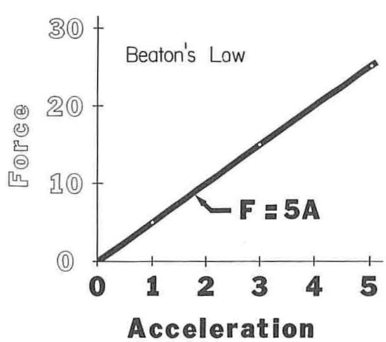


Figure 5.

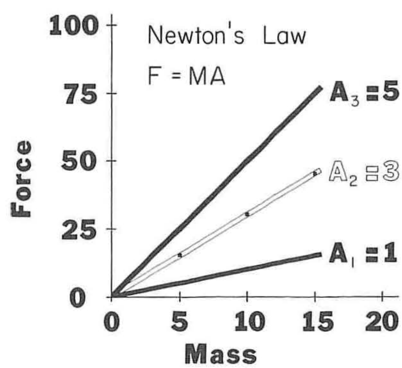


Figure 6.

struck his head. That year he went to the Fruit Research Board and reported that empirically grapefruit were more dangerous than lemons. After several more years of study, while obtaining a very sore noggin, he also refined his data as shown in Figure 4. From this he deducted Hudson's Law: Force is equal to a constant of 3 times the mass of the falling object. He dutifully went back to the national convention and reported these findings.

Not long thereafter young Johnny Beaton, living out in California, lay around under the date trees and grape arbors. He noticed with brilliance equal to Hudson's that when dates falling from tall trees struck his head they hurt much more than grapes falling from the low arbors. He also ran a scientific experiment and reported that the height of the tree was very important. After studying the data (Fig. 5), he noted carefully that the force of a falling object is really equal to a constant, 5 times the acceleration of the object. He dutifully went to the national convention and reported Beaton's Law, which seemed to discredit, by innuendo although not directly, Hudson's Law.

Shortly thereafter young Newton, who lived somewhere in the northwest among the apple trees, often sat to think under small apple trees and large apple trees, under trees growing big apples and little apples. He noted very astutely that the pain due to an apple hitting his head depended on the size of the apple as well as the height of the tree; however, the problem was too complex for easy solution. He promptly called in 3 of his friends (Paul Irick, Virgil Anderson, and Jack Youden) who considered the problem with him in some detail. Finally, an appropriate experiment was designed and apples of various size were dropped from various heights onto poor Isaac. Figure 6 shows very succinctly the data that resulted. Lo and behold, the mass really did not govern the results directly nor did the acceleration. Newton's Law was therefore born: Force is proportional to mass times acceleration. When this result was reported at the national convention, Beaton and Hudson were discredited, and it was reported that they subsequently have spent their declining years playing with dirt, cement, and asphalt.

To me this myth illustrates why our literature is full of contradictory conclusions. Like the blind men and the elephant, each of us deals with one part of the problem, such as the mass, while ignoring an equally important part, such as the acceleration.

A serious example is shown in Figure 7. If I looked only at an asphalt content of 7 percent, I would report that fine gradations are better than coarse gradations. However, at an asphalt content equal to 4 percent, the exact reverse is true. At a recent conference, a colleague of mine reported that the tensile strength of asphaltic mixes did not depend on gradation. Figure 8 shows the experiment design that led to his conclusions. In the meantime, we ran a rather large experiment involving 7 variables, one of which was gradation. The results of these tests show that, in truth, gradation has no direct effect. Figure 7 shows, however, an important interaction effect, and the tensile properties do vary with gradation because the effect of asphalt content changes as gradations get finer because more asphalt is absorbed by the mix.

Table 1 gives the factor space over which an asphalt stabilization experiment is to be conducted. Seven factors are included at 2 levels such. Figure 9 shows another presentation of the same factor space. In the figure, a better relationship can be seen among the variables because all possible combinations of the variables are shown and there is one block for each combination in the factorial. Furthermore, this form can be used to collect data. The answers for a specimen applicable to a particular set of factors can be written down in that block. If the rows and columns are summed, you have a quick look at the data, and it is possible to make quick estimates of factor effect.

If it is impossible to conduct as many tests as you desire, such as in the case of the factorials shown in Figure 9—128 specimens plus some replicates—we can run a special experiment taking some carefully selected samples. This is called a fractional factorial. Figure 10 shows a one-quarter fractional factorial, that is, one-quarter of the total number of blocks. It is not always desirable to take partial factorials; however, under certain circumstances they can be especially useful in cutting down on the size of an experiment while obtaining satisfactory results.

If a quarter fraction is too small, then a half fraction, as shown in Figure 11, can be tried; this is the first quarter plus the addition of a second quarter. You can see in Figure 11 the symmetry in the selection of samples to be taken. There are equal

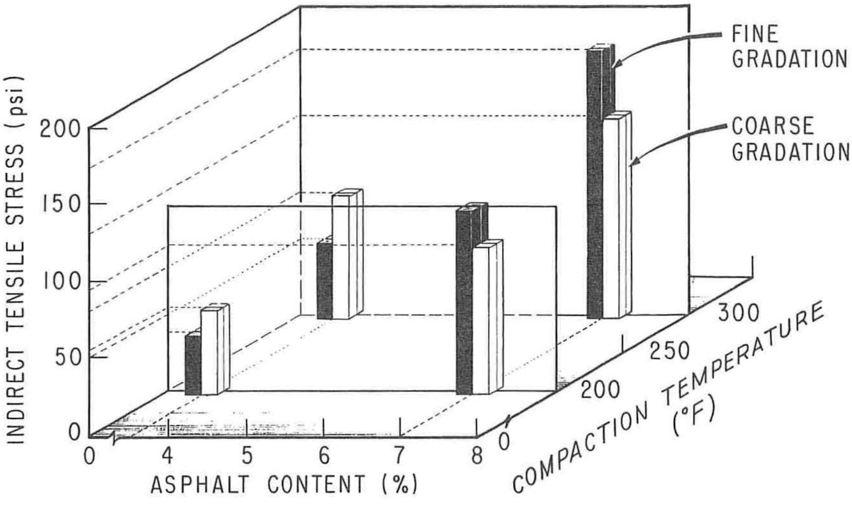


Figure 7.

numbers of all factors involved in the samples to be chosen so that there is balance within the experiment. Certainly there is not as much information as in a full factorial, because there are many fewer degrees of freedom in the experiment.

Table 2 gives the factors in a cement treatment experiment involving 5 factors at 3 levels and 4 factors at 2 levels each, or 5,832 specimens, an almost impossible number to deal with. In this case it is almost essential to deal with a one-quarter or

Aggregate Type	Basalt			Limestone			Granite			Gravel		
Asphalt Type / Gradation	40-50	60-70	85-100	40-50	60-70	85-100	40-50	60-70	85-100	40-50	60-70	85-100
Coarse									6.0			
Medium		5.3-8.7				4.7	6.0	6.0	5.2 & 6.0			4.6
Fine									6.0			
X							7.9					

Figure 8.

even a one-eighth fractional factorial. As a matter of fact, we ran an even more complicated experiment by breaking the experiment up into 3 separate parts, but that is too complex to discuss here.

Let us turn our attention now to the results of some of these experiments. Figure 12 shows what statisticians call a main effect. This is the effect that a particular variable, in this case molding water content, has on the results of a test, in this case, indirect tensile strength. As we can see, increasing molding water content from 3 to 7 percent increases tensile strength from 60 to 200 psi, We might write an equation for the effect in the form

$$T = C_O + C^1W$$

This is the type of effect that engineers most often model.

Figure 13, however, shows a 2-factor interaction. Unfortunately, if we look at the main effects and think that we know what the effect of molding water content is on tensile strength, we will be badly mistaken, because molding water content also interacts with gradation to affect the results. That is, the effect of water content is greater on fine gradations than it is on coarse gradations. An interaction is the term we use to describe the cross-product terms in a mathmatical model when the effect of one factor depends on the level of another factor in the experiment.

As if that were not complicated enough, there are sometimes 3-factor interactions present, which really causes problems. The 3-factor interaction involving water content, cement content, and type of curing is shown in Figure 14. As you can see, the

			AGGREGATE	Limestone				Gravel			
			GRADATION	Fine		Coarse		Fine		Coarse	
CURING TEMP., °F	COMPACTION TEMP., °F	MIXING TEMP., °F	ASPHALT CONTENT, % / VISCOSITY (Space)	AC5	AC20	AC5	AC20	AC5	AC20	AC5	AC20
75	200	250	5.5								
			8.5								
		350	5.5								
			8.5								
	300	250	5.5								
			8.5								
		350	5.5								
			8.5								
110	200	250	5.5								
			8.5								
		350	5.5								
			8.5								
	300	250	5.5								
			8.5								
		350	5.5								
			8.5								

Figure 9.

TABLE 1

FACTORS INCLUDED IN ASPHALT STABILIZATION EXPERIMENT

Factor	Level: Low	Level: High
Aggregate type	Crushed limestone	Rounded gravel
Aggregate gradation	Fine	Coarse
Asphalt viscosity	AC-5	AC-20
Asphalt content, percent	5.5	8.5
Mixing temperature, deg F	250	350
Compaction temperature, deg F	200	300
Curing temperature, deg F	40	110

TABLE 2

FACTORS INCLUDED IN A CEMENT TREATMENT EXPERIMENT

Factor	Level: Low	Level: Medium	Level: High
Molding water content, percent	3	5	7
Curing time, days	7	14	21
Aggregate gradation	Fine	Medium	Coarse
Type of curing	Air dried	—	Sealed
Aggregate type	Gravel	—	Limestone
Curing temperature, deg F	40	75	110
Compactive effort	Low	—	High
Type of compaction	Impact	—	Gyratory shear
Cement content, percent	4	6	8

effect of cement content is much stronger at high water contents than at low water contents, but it is also stronger in general for sealed than for air-dried specimens as shown by the greater height of the black columns. Thus we see that we cannot show the effect of water content alone, because it causes other effects in combination with other factors; in this case, cement content and type of curing.

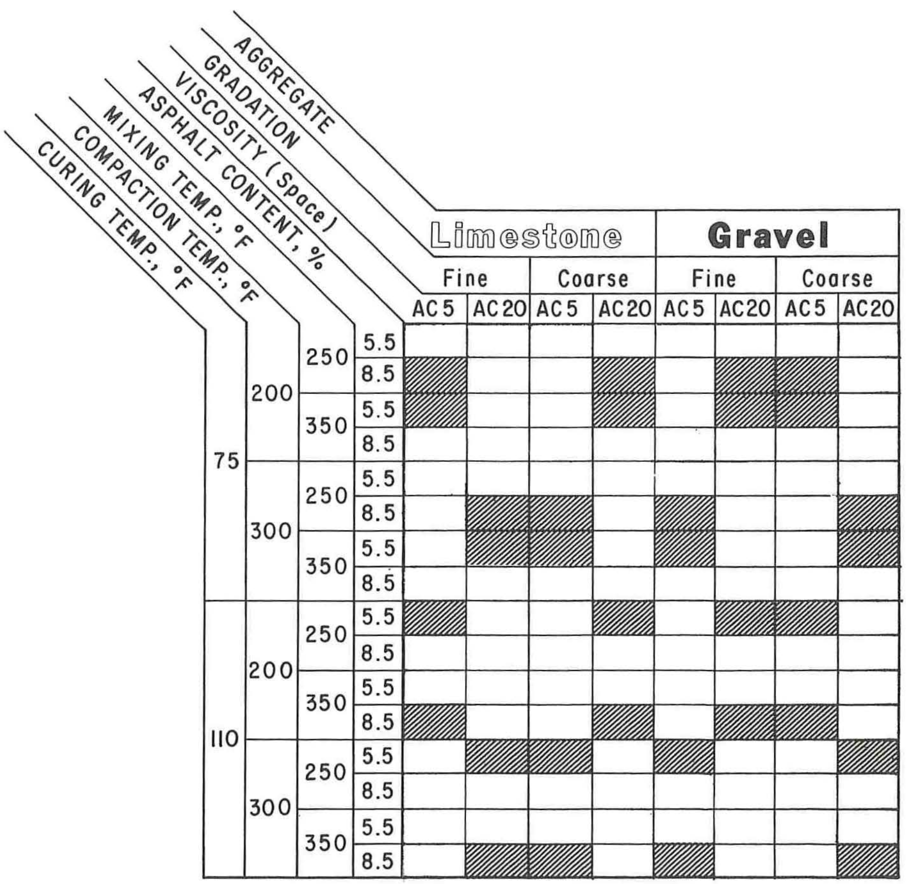
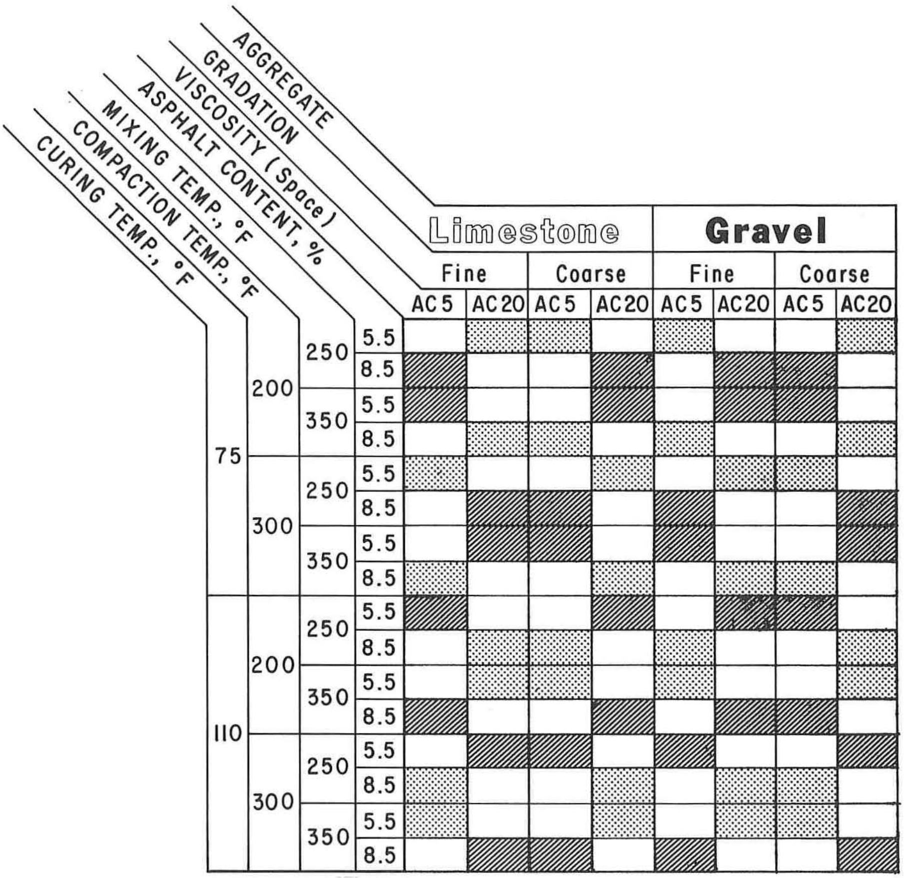


Figure 10.



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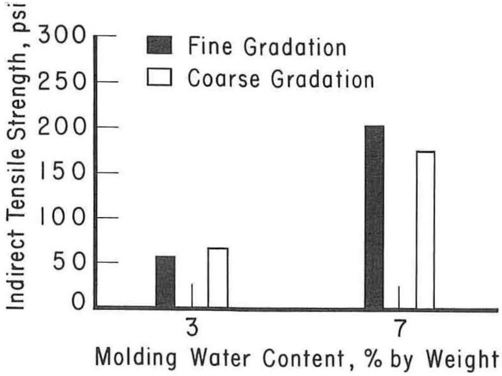

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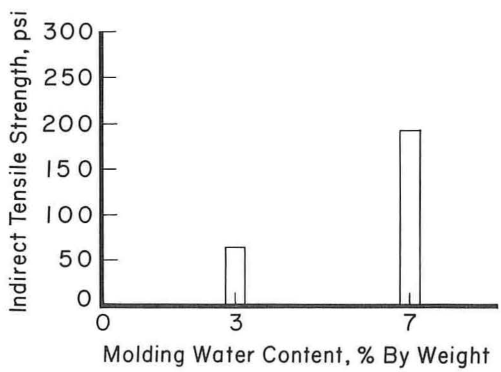

Figure 13.

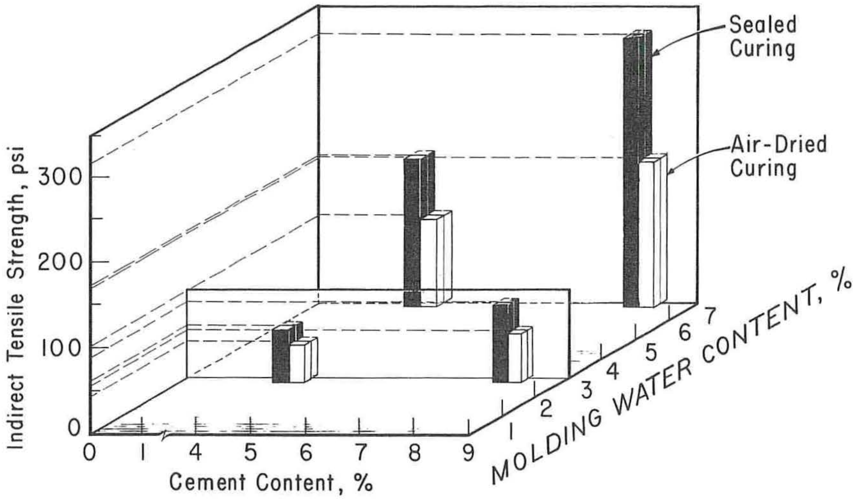

Figure 14.

I would summarize this discussion as follows:

1. The design of experiments forces an explicit look at the problem, the factors involved, and the levels of interest. This look improves our understanding of the problem. I have seen this so often with graduate students. They struggle for months to define and design their experiments, until they get a little exasperated with me because I do not do it for them. After they get the experiments designed, however, they find that the completion of the tests and the final analyses become much easier.
2. On complex problems, as most engineering research problems these days are, statistics is essential for getting the correct information from the test, getting the most information for your money in an experiment, and understanding quantitatively the findings of an experiment, that is, how good the answers are.
3. On very complex problems, the assistance of a statistician can be helpful; in fact, it is sometimes almost essential. However, for many simple problems, and after some consultations with a statistician, most engineers can, with the use of a good statistics book and some hard work, because reasonably good at designing and analyzing simple experiments.
4. Experimental design can be very valuable in conducting laboratory research experiments.

Practical Problems in the Design of Field Experiments

JOHN L. BEATON, California Division of Highways

•CONSIDERATION of the basic principles of experimental design as well as the selection of statistical methods for data acquisition and analysis is mandatory in the planning phase of any experiment. This is true whether it is to be performed in the laboratory or in the field.

There are certain differences, however, between laboratory and field research that must be considered in the formulation of a field research program. These differences primarily result because the environment is beyond control of the researcher. However, of almost equal concern are the management problems, particularly personnel, that occur in the field. If these factors are not recognized and considered in the experimental design as possible sources of variation, their effects will most certainly be confounded with the response of the material, condition, or property under investigation.

This confounding of the effects of uncontrolled variables with controllable and measured parameters under test will produce invalid quantitative data; and in addition, because of possible interaction among these effects, statistical tests may erroneously indicate that significant differences are occurring for the conditions being investigated. In reality, however, these differences may be insignificant. Usually, the effect of this sort of confusion is to limit the ability to detect changes in test parameters when they do occur.

TWO BASIC CATEGORIES OF FIELD EXPERIMENTS

At this point, a look at 2 basic categories of highway field research is in order. The first category includes those experiments in which the uncontrolled variables are largely confined to the intrinsic properties of the natural environment. Typical experiments might range from weathering of paints or signing materials to in situ testing of rock or soil for evaluation of new test devices. This category of experiment is usually characterized by a relatively relaxed time schedule. The investigator usually has direct control over project labor, administration, and progress. Many such projects are relatively inexpensive, and most can be repeated with little deleterious change in the uncontrolled variables or increase in cost.

The second basic category encompasses those projects that are associated with the construction of a highway facility or appurtenance. Typical work in this category might range from the instrumentation of an orthotropic bridge for observation of stress patterns to the measurement of pore pressure variation in a soft foundation due to embankment construction. Experiments in this category are often characterized by dependence on a contractor's time schedule. The investigator usually lacks direct control over project labor, administration, and progress. Such projects may be quite expensive and are usually impossible to repeat because the uncontrolled variables are unique to the particular location or structure and redoing an entire structure or even a portion would be prohibitively expensive.

It is evident that research falling in this second basic category will require a greater safety factor, solely because of the irretrievable nature of the experiment. By a greater safety factor I mean, for example, 1 or 2 levels of redundancy for critical

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data points to guard against data loss due to failure, allow better statistical averaging, and provide better application of tests for significance.

Some of the other problems occurring in this type of research are primarily administrative in nature. These administrative problems, however, do affect the design of the experiment. The effects are mainly financial and psychological. The psychological effects will be mentioned later under human factors as uncontrolled variables. From a financial standpoint, the administrative nature of such a project causes an excessive expenditure of research money. This money is needed not only for extra instrumentation but also for the extra man-hours for standby time to match the schedule imposed by the contractor or weather.

Provisions for adequate working time to install the research facilities, physical help from the contractor's personnel, and subsequent protection of the research facility from the contractor's operations are a necessary part of the contract. The lead time for this type of research is, therefore, substantial and must be considered in the early planning stages.

Once the contract is let, prosecution of the research is greatly facilitated by conferring jointly with key personnel of the contractor and the project engineer. Administrative problems such as work sequence, payment for extra work, and joint and individual responsibilities can be worked out. Some of the actual physical steps in the research should be kept flexible up to this point to allow incorporation of ideas that may be presented by the other conferees. If the researchers earnestly seek to enlist the cooperation and interest of these people, the research will be greatly aided. Research personnel who like to project an "ivory tower" image will be a detriment to this sort of conference.

An often justifiable expense for field experiments in this second category is the employment of a field coordinator for the research. This individual should be selected from the highway project personnel. He acts as a go-between for the researchers and personnel of both contractor and project once the project is under way. Mandatory personal attributes include statesmanship, an appreciation for research, a well-developed sense of humor, and an excellent knowledge of construction practice. Such a person can be worth many times his salary in smoothing the path for research personnel.

During the progress of the research, both the project engineer and the contractor should be kept informed of significant and interesting developments. When the report is written, acknowledgment of their assistance should be made and they should receive copies of the report. Recognition of this sort will go a long way toward improving both present and future research climate.

THE NATURE OF UNCONTROLLED VARIABLES AND OTHER PROBLEMS

Uncontrolled variables affecting either or both of the 2 basic types of field experiments will normally fall into 1 of 4 general groups including environmental factors, human factors, hardware factors, and construction methods. Obviously, all of these variables will not apply to all field experiments and, in many cases, there will be considerable interrelationship among variables.

Some of the problems, such as accidental or malicious damage to the experiment, cannot be dealt with statistically as can the unknown or uncontrolled variables. These problems must be considered, however, in planning the experiment.

Environmental Factors

Environmental factors are normally uncontrolled or only partially controlled in most field research. Included in this general group are obvious things such as temperature, relative humidity, wind, vibration, anisotropy of soil deposits, and corrosive atmosphere or water. Also in this group are less obvious but diverse factors such as damage to the experiment due to falling rock or earth slope failures, biological damage to instrumentation, changes in water table due to pumping or irrigation, and changes in geometry with increase in fill height. These are just a few examples.

Human Factors

In field research the investigator may have to consider the ability or desire of a craftsman to build a facility to the tolerance required for the experiment. Conversely, tolerances tighter than normal may be obtained because of the presence of a research observer. When the progress of the work is controlled by a contractor's operation, research personnel are often placed under stress because of unpredictable variations in the time schedule. Also, research that is part of such a highway contract is often a "poor relation" in the eyes of project and contractor's personnel. Morale and efficiency of the research team suffer as a result. These and other similar psychological factors have a direct bearing on the reliability of the acquired data.

Adverse working conditions such as rain, snow, and mud will doubtless affect the efficiency and performance of the researchers. Often the nature of the field experiment requires considerable assistance from personnel who are not research-oriented. In these cases, communication, or rather the lack of it, can lead to invalid data. Careful selection of research personnel and assistants is indicated. In addition, enthusiasm for the project must be instilled in everyone involved.

Vandalism can be a nightmare to the researcher in the field. An average marksman with a small caliber rifle can reduce an unprotected installation to junk within minutes. Careless exposure of copper and other marketable materials may encourage surreptitious salvage operations.

Hardware Factors

Hardware factors should be evaluated prior to the data-acquisition stage. Instrumentation should be designed for system accuracy and repeatability, neither of which should deteriorate under field conditions. Suitable backup for critical data-acquisition methods must be provided. Experiments with complex instrumentation may require automatic data-acquisition equipment. Precautions for on-the-spot maintenance and backup must be taken. Power must be reliable. In some cases, such complex projects entail considerable expense for the physical appurtenances necessary for adequate data acquisition. The inability to anticipate the magnitude of error inherent in a field measurement technique may invalidate the data. Inherent error of an inappropriate measurement technique may approach or exceed in magnitude the change in the test parameter. Some of these considerations may seem quite basic, and they are; but it is surprising how often they may be overlooked.

Construction Methods

Construction methods that constitute accepted highway practice must be considered in research design. The investigator can expect to encounter resistance if he proposes new methods entailing the use of nonstandard equipment or unfamiliar methods. When new methods, procedures, and requirements are included in the contract, shoddy workmanship is likely to result unless adequate preparation is made.

DESIGN COMPENSATION FOR UNCONTROLLED VARIABLES

Control sections, or sites, are often included in a test area to isolate and evaluate the source or cause that may have an influence on the response of the material or condition being investigated. The number of control sections may be limited by economic considerations but ideally should be distributed or selected at random throughout the test area, dependent on the variability of the effects to be isolated. Although the main test parameter is normally held at a single level for all control sites, additional control sites with the test parameter at other levels should be considered if there is reason to believe an interaction exists between it and uncontrolled sources of variation.

Measurement of the magnitude of a known uncontrolled variable and compensation for its effect may sometimes be successful. The compensation may be applied theoretically if there is known to be good correlation between the variable and its effect on the experiment. Usually, however, an empirical correlation is established. In most

cases, it is advisable to perform pilot studies in preparation for a full-scale field investigation. In this manner, certain conditions that cannot be controlled in the field may be synthesized in the laboratory to determine if these uncontrolled conditions either cause predictable results or significantly affect the purpose of the research. Although pilot tests in the laboratory will result in pseudo data values that may or may not be the same as those found in a field investigation, the information obtained can be quite valuable when the field experiment is designed.

Statistical averaging through replication of instrumentation or data acquisition within test sites, replication of test sites within an area, and replication of readings by different observers or equipment should be considered. Replication and randomized treatment provide a means to determine the reliability of acquired data and will tend to negate certain uncontrolled variables that are dependent on the site, operator, or equipment and will allow statistical treatment of them in the analysis.

Factorial design using analysis of variance principles allows greater efficiency in the use of observations and greater precision with less replication than the classical experiment. Random sequences of observations relegate the effects of certain uncontrolled variables to the residual or error term where they are not confused with the test parameters and their contribution to experimental variation can be estimated. With the advent of greater computer usage, analysis of variance technique is applicable to larger, multivariable investigations.

SUMMARY

In summary, there are 4 inseparable phases that must be carefully considered in any good field experiment. There are experimental design considering statistical implications, execution of the field experiment, analysis of data, and implementation of findings. Of these, the initial planning and design phase is almost invariably the most critical. The damage resulting from a poor design is irreparable; no matter how ingenious the analysis, little meaningful information is ever salvaged from data derived from poorly planned experiments. On the other hand, if the design is sound, then even "quick and dirty" methods of analysis can yield a great deal of useful information. It might be stated that the need for careful planning and design is even more acute for field experiments than for laboratory experiments. The additional cost of doing field work and the necessity to work with individuals who are not normally associated with research work make it imperative that all phases of the work be carefully planned and coordinated. The experimental design procedures that are commonly accepted in laboratory work must be extended into field operations if the results are to be meaningful. In the California Division of Highways we have learned many of these lessons the hard way, primarily through experience. However, through training programs and the influx of engineers over the past several years with formal training in statistics and experimental design, it is now routine to fully consider all the essential elements of experimental design, including statistical considerations, from the inception of a research project to its culmination in a better highway project.

Sample Survey Design

A. L. FINKNER, Research Triangle Institute

•MANY PROBLEMS in highway transportation and safety are not amenable to controlled experimentation, and the investigator must resort to observational studies. In other words, the phenomenon under scrutiny must be examined and measured as it exists and without disturbing it. Observational studies have less investigative power than controlled experiments; although relationships can be established, it is often quite difficult to assign cause and effect. The techniques used most often to study these phenomena are commonly referred to as sample surveys.

Surveys may be classified into 2 broad general types or groups: descriptive and analytic. The investigator in the highway transportation field makes use of both types.

As it implies, the descriptive survey provides a description of the population from which the sample is drawn. A well-designed sample survey not only provides estimates of the various characteristics of the population under investigation but also should provide estimates of their precision as well. The results of descriptive surveys are often used as a basis for administrative action. They also may be exploratory in nature and used to develop hypotheses that will be tested by techniques with more investigative power.

An example of a descriptive survey is a litter composition study designed by Research Triangle Institute under the auspices of the Highway Research Board and Keep America Beautiful, Inc. The data were collected through the cooperation of the state highway departments in the various states that participated. Here the objective was to estimate the composition of highway litter so that the various industries contributing the products that ended up as litter could be made aware of the magnitude of the problem. Although the distributions by various domains were compared, the study was not designed to measure associations among the various variables.

Analytic surveys attempt to go beyond pure description and to determine relationships or test hypotheses. Here, for example, we may wish to test the efficiency of driver training or safety belts on reducing accidents or serious injuries. Although it might be ideal to be able to select a sample of young men and women of a certain age, match them with respect to certain variables, assign them to driver training or no training at random, and then measure their safety records under the same conditions over a period of years, such an ideal is unattainable. Therefore, we must resort to other techniques to obtain answers to the questions raised. Cochran (1) discusses the problems in planning observational studies and some of the current strategies in overcoming them. The problems can be classified into those encountered in setting up comparisons, dealing with disturbing variables, going from measures of association to the elucidation of causation, generalizing from the sample to the population, measuring, and considering multiple variables.

For purposes of illustration, consider 2 problems: (a) comparison of the number of serious accidents among safety belt users and nonusers, and (b) effect of various community campaigns on the incidence of drinking drivers.

In the first investigation, we must measure at least 2 quantities. We must first have an estimate of the number of serious accidents that occur to both safety belt users and nonusers. There are certain problems encountered here. The definition of a serious accident may be troublesome. In some accidents the determination will be obvious, but

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border-line cases may be difficult. There also may be a problem of underreporting but, in the main, these problems are tractable. The sample is usually defined in time or space or both; i. e., certain areas, such as counties or states, may be selected and examined at random times.

Before any meaningful comparisons are possible, however, an attempt must be made to match, at least on major variables. One obvious major variable is the number of drivers in the 2 categories and the number of miles driven by each, or the number of driver-miles. This is sometimes referred to as exposure and must be estimated from an entirely different type of survey. At the time exposure is estimated, other relevant variables should be measured. These include descriptions of the driver and vehicle and characteristics of the highways and the environment. Of course, these same characteristics should be enumerated for each serious accident. Even then conclusions may be tenuous. For example, if all nonusers are driving old cars that were manufactured before seat belts were required, the results could be the result of the age of the car and not the failure to use seat belts unless this kind of factor is adequately assessed. Thus, in studies of this kind, 2 surveys are required, one to estimate the numerator of a variate and one to estimate the denominator; and both are equally important.

In the second problem, let us consider some proposals being made to test the effectiveness of various countermeasures to drinking and driving. Howard Pyle, National Safety Council president, is quoted as saying that attempts to talk people out of drinking and driving have failed. The approach now seems to be to try to teach the people the amount of alcohol they can consume and still drive safely. Studies are being designed in several major cities in the United States to evaluate the effectiveness of drinking-driving countermeasures. Some countermeasures that have been proposed are (a) a program of public information and education; (b) a program of strict law enforcement in conjunction with special handling of cases by the courts; and (c) programs a and b operating simultaneously. It is hoped that the effectiveness of these countermeasures can be evaluated and that, if any show promise, they can be adopted on a larger scale.

First assume that we have only one countermeasure and one city. The so-called before-and-after type of study is often employed in situations of this kind. At a minimum, the incidence of drinking drivers must be estimated and the principal disturbing variables such as exposure by various characteristics of the driver, vehicle, highway, and environment must also be measured. At an appropriate time after the introduction of the countermeasure, the same variables are measured again. This enables us to examine whether changes in the drinking driver incidence have occurred over and above those expected from changes in the disturbing variables. The estimate of the effectiveness of the particular countermeasure is subject to the following 2 types of bias: (a) people's behavior immediately prior to the program might be affected by the knowledge that the program is about to be initiated; and (b) some disturbing variables that affect time changes may be unknown. The first type can be controlled in this case by refusing to allow any publicity prior to the introduction of the countermeasure. The second type is more serious and may be impossible to control.

Now, if it is possible to conduct the same program in 2 cities that are somewhat evenly matched with respect to disturbing variables, it is possible to select one city at random to be the programmed city and the other to be the control. Even if they cannot be matched on the disturbing variables, it is usually possible to adjust for such differences. Then the differences between the before-and-after measurements in the 2 cities are compared. Although we still have the problem of unknown disturbing variables affecting the 2 cities differently, the probability of success in measuring the effectiveness of the countermeasures is greatly enhanced by the addition of the second city.

When we have only 1 city and 3 countermeasures, like those mentioned earlier, our difficulties are compounded. Not only do we have the same problem of unknown disturbing variables, but we have an unknown contribution from a carry-over effect from the previous countermeasure when a new one is adopted. Again, these effects can be best measured by adding cities that are as alike as possible and by applying the principle of cross-over designs from the field of experimental design. The order of the "treatments" or countermeasures must be designed so as to permit estimates of the carry-over effects and then the various orders assigned at random to the cities.

The estimates of the incidence of drinking drivers also deserves some attention. Roadblocks can be set up at random points and at random times. However, the driver can refuse to be examined, introducing the possibility of a bias of nonresponse. So long as the nonresponse rates are approximately the same in each period of countermeasure activity, this bias probably can be ignored.

In summary, analytic surveys or observational studies should be designed as carefully as possible so as to minimize the bias from potential sources and at the same time to allow as much precision as possible. As near as possible, the population sampled should be the population about which inferences are to be drawn. If these inferences are to have validity, probability samples should be used wherever possible. Disturbing variables should be identified, and attempts to match or adjust for the most important of these should be made. In making the transition from measures of association to causation, the investigator will usually have evidence from a heterogeneous collection of results of varying quality. He must weight these results, giving low weight, of course, to poor quality information. Finally, he should state his judgments about conclusions clearly, attempting to be as objective as possible.

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1. Cochran, W. G. The Planning of Observational Studies of Human Populations. Jour. Royal Statistical Soc., 1965.

Part 2
Foreword

The paper by Hong, Schwar, and Talbert is appropriately related to the preceding papers in that it discusses the organizational framework within which research projects are undertaken. The authors discuss concepts and methods for highway transportation research and development programs and present structures for both organizing and programming research and development within government at all levels and within academic, industrial, and other types of organizations.

A New Approach Toward Formulating Research and Development Programs

H. HONG and J. F. SCHWAR (deceased), Ohio State University; and
L. O. TALBERT, Ohio Department of Highways

This paper discusses concepts and methods for structuring R&D efforts in highway transportation together with techniques for establishing short- and long-range dynamic R&D programs for the purpose of guiding future R&D efforts in a systematic and well-coordinated manner. A new R&D organization structure is proposed based on the concept of "mission-oriented systems approach." A hierarchical structure of 3 levels is developed in terms of strategic, tactical, and action models for the purpose of programming R&D. These structures are used to develop concepts and methods for developing dynamic R&D programs based on R&D needs and resources. These program techniques are helpful in providing systemized procedures that will ultimately help guide, coordinate, and promote positively defined goals.

•THE MAJOR GOVERNMENTAL AGENCIES, universities, industries, and research-oriented organizations with an active interest in highway transportation research are confronted with a complex and long-standing challenge, namely, to solve the many-faceted problems of highway transportation. What logical research and development programs should be formulated to solve these problems? What logical allocation of limited resources should be made to support such R&D programs?

A review of past and current research activities of a number of research organizations indicates that (a) each organization tends to have its own method of formulating its R&D program, which is generally dependent on the nature of the organization, its policies, the internally and externally imposed constraints, and the size and nature of available and future resources; and (b) there has been a great deal of fragmentation, duplication, and lack of correlation and direction in the overall R&D program and some waste of research effort.

One of the consequences of this unstructured approach to R&D in the past has been an absence of tangible benefits commensurate to investment. It is evident that there must be better organized and systemized procedures and structures through which the entire effort of R&D in highway transportation can be guided, coordinated, and promoted toward positively defined goals. This paper is confined to the development of concepts and methods of R&D program formulation. These concepts and methods are especially important from the viewpoint of subsequent detailed development of R&D programs.

The problem of R&D program formulation is conveniently examined within the framework of the following objectives:

1. To develop concepts and methods for structuring R&D efforts toward improvement of highway transportation; and
2. To develop concepts and frameworks for establishing short- and long-range dynamic R&D programs, guiding future R&D efforts in a systematic and well-coordinated manner, and maximizing the benefits resulting from R&D.

While these objectives can be spelled out only in the broadest terms, the criteria that must be met by the resulting R&D programs can be identified more specifically as follows:

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1. Provision for both theoretical (new concepts) and applied research (new methods and development);
2. Provision for the translation of theoretical research results into practical use;
3. Use of systems concepts to permit a better understanding of the relationships among many research areas;
4. Capability of development and expansion within the framework of overall programs already established by governmental and industrial agencies;
5. Realism in terms of availability of physical, fiscal, and manpower resources;
6. Realism in terms of priority and scheduling; and
7. Compliance with the research institution's policies.

The overall significance of a framework within which R&D programs can be developed lies in the end product, namely, in a sound base and structure for the orderly expansion and development of both existing and future research and development programs. This is of particular importance when viewed against the complexity and magnitude inherent in future research efforts required to meet the challenges of tomorrow's transportation requirements.

This method of procedure includes 2 phases: (a) development of concepts and methods of formulating R&D structures; and (b) development of concepts and methods of formulating dynamic R&D programs. These phases, while described separately, are not mutually exclusive. On the contrary, they are very much interrelated.

DEVELOPMENT OF CONCEPTS AND METHODS OF FORMULATING R&D STRUCTURES

A prerequisite to developing R&D programs in highway transportation is to establish a number of R&D structures as a guide to the orderly development of such programs. There are basically 2 types of R&D structures that are useful toward this end: (a) the organization structure and (b) the program structure.

Organization Structure

The organization structure is mainly concerned with the arrangement of various, often diverse, R&D functions and activities into an integrated, coherent system with each part working toward the common organizational goal (in this case, improvement of the services provided by the highway transportation system) and each component represented in terms of its ultimate performance within some large system. This type of systems organization or classification is essential for the development of the R&D program structure and, indeed, for successful R&D performance.

The underlying concept of the evolvement of a highway transportation systems research structure (or a dominant requirement of this R&D organization structure) is a mission-oriented systems approach as shown in Figures 1 and 2. This new approach is quite different from the traditional subject-oriented R&D classification (as in the Highway Research Board subject organization) in that the various elements that make up the research effort are structured to accomplish a positive mission. A structure of this nature involves identifying all of the necessary research elements, activities, and their relationships; structuring these activities into a proper hierarchical framework; and sequencing these activities in such a manner as to be useful toward accomplishing a positive mission. Some other characteristics of a mission-oriented structure include clear purpose, clear logic, interrelationship, coordination, logical grouping, coherency, flexibility, and convergency toward a mission or an objective.

Based on this concept, 5 system elements of highway transportation systems research were developed (Figs. 1 and 2). These are administration and management (or systems management), systems planning, systems operations, materials, and structures. (The system elements of materials and structures could have been combined to form "systems physical facilities." The reason for not combining them is that the expertise necessary to develop an R&D program in these system elements is quite unique and often mutually exclusive; i.e., a materials specialist may not be a specialist in pavement structure and vice versa.) These 5 system elements not only constitute the essential

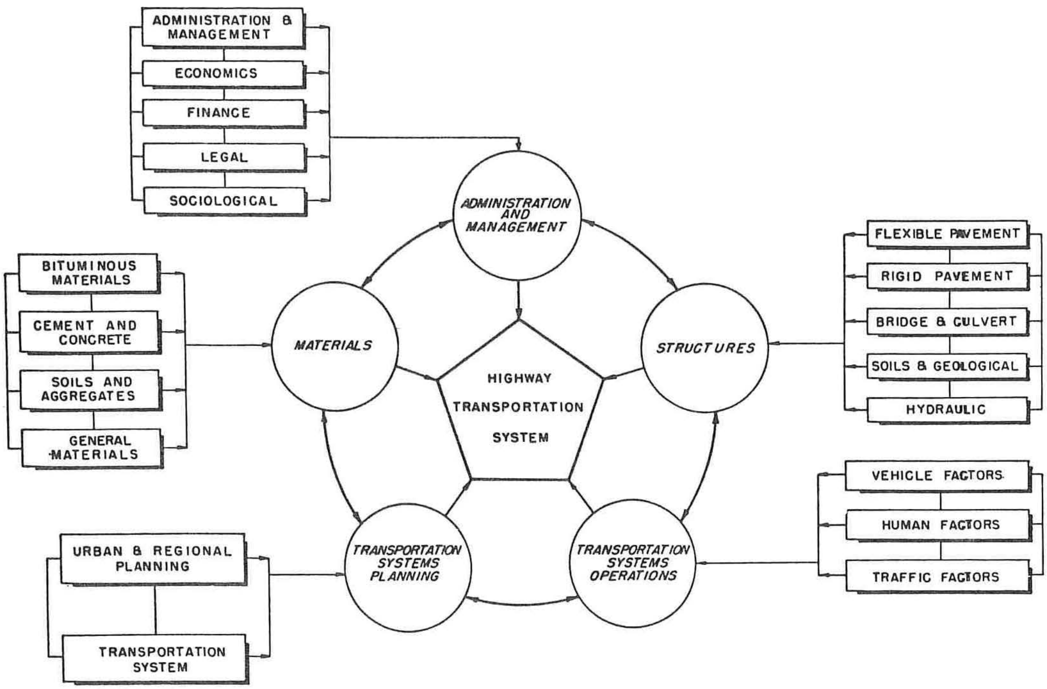

Figure 1. Structure for highway transportation research.

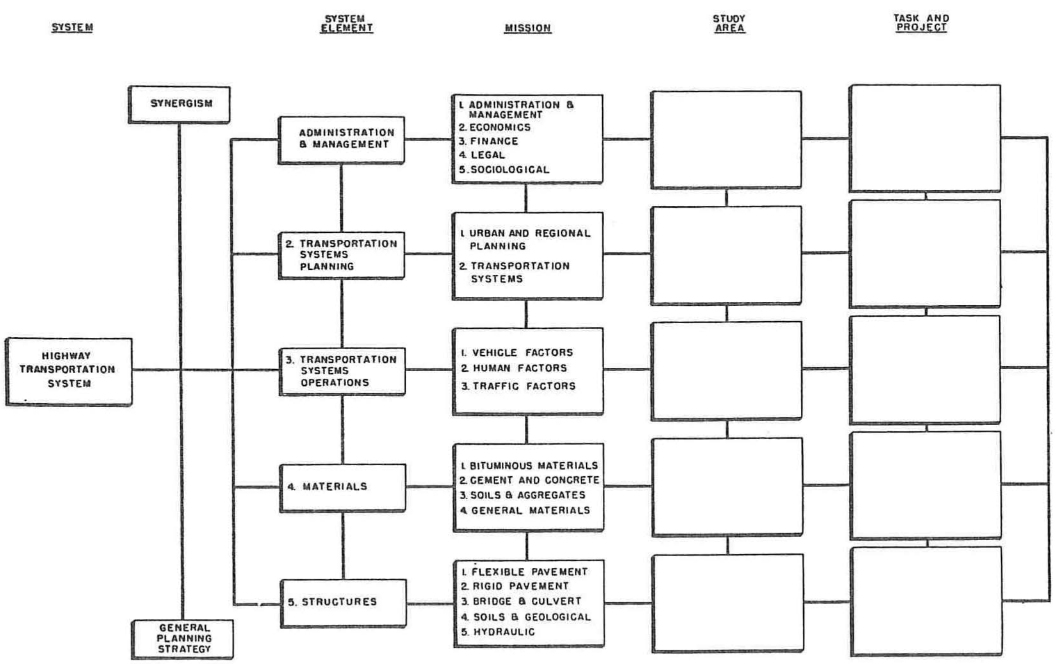

Figure 2. Highway transportation system research model.

core but also cover the entire spectrum of highway transportation R&D as seen today and envisioned for the foreseeable future. These system elements were selected not for the purpose of isolating any of the R&D components but for the purpose of forming viable systems components that demonstrate the distinct characteristics of highway transportation systems research and the need for an integrated synergistic approach to R&D program formulation and R&D performance.

Each system element consists of a number of missions that characterize its vital role in highway transportation systems R&D structure. There are a total of 20 missions under the 5 system elements (Fig. 2). (Actually, each mission should read, for example, "improvement of the performance of flexible pavement," "improvement of traffic factors," and so on. However, for brevity, only the key words are given.) A mission provides a positive research goal to be accomplished. It is an essential hierarchical unit that serves as a basis for establishing R&D orientation goals and systems integration. A mission also represents expertise in the existing R&D discipline structure that could participate in the R&D efforts of its own specialty and capability.

Each mission, then, is comprised of a number of study areas or problem areas. For example, a study area within the traffic factors mission might be improvements in street network operation. This level of the R&D systems hierarchy may be considered as the working unit that specifies the positive objectives to be accomplished. An R&D program is formulated to accomplish these specific objectives. These problem areas may be of an applied or a theoretical nature. They may be short- or long-range R&D activities. They may be given priorities based on some logical priority criteria. Incorporation of the problem areas into the program structure will be described later.

Each study (or problem) area is then broken down to the next lower hierarchy, namely, a number of tasks and projects, and structured in terms of phases and flows of R&D activities that are required to accomplish the stated objectives.

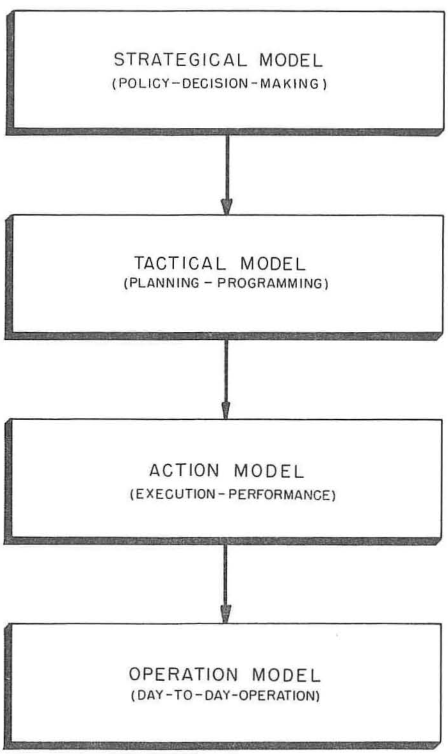

Figure 3. Hierarchy of R&D planning and programming.

In the formulaton of R&D programs on the level of tasks and projects under a given problem area, the project or task selection is not limited to that particular mission area under which the problem area is considered and for which the R&D program is being developed. On the contrary, tasks and project selections for one particular objective or one problem cut across the mission boundaries and thus attain the characteristics of a systems approach. All of the relevant system components that define the problem and the major interactions are integrated into the problem area R&D formulation.

In summary, an organization strugture provides a primary framework and basis for a systems approach in both R&D program formulation and R&D performance.

Program Structure

In addition to the R&D organization structure described, there is a need for an R&D program structure to describe and to program various R&D activities that will achieve the stated goals and objectives. An R&D program structure, in essence, provides 3 levels of hierarchy with respect to the orientation, thrust, activities, and structures. The structure that describes this hierarchy consists of strategic, tactical, and action models (Fig. 3). A fourth model (operation model) is not a

program model but a day-to-day R&D operation model and is not considered at this time.

The basic concept underlying this program hierarchy is that, if the basic strategy of R&D, either on a national or local level, for a given mission and for highway transportation research as a whole is established properly, then there is a strong probability that present and future R&D efforts programmed in terms of the tactical and action models (which are developed within the framework of the R&D strategy) have at least a fair chance to be sound and effective and also may be expected to maximize the return on R&D investment. If the basic strategy is not properly formulated, however, the tactical and action models would not only be invalid but would also yield the least amount of return.

Thus, it is paramount to develop a series of sound R&D strategies to guide the R&D activities on the national level to promising directions and to successful results. The task of developing these strategies rests on the administrators of federal and state governments and research institutions. These strategies, once established, should be reviewed periodically in the light of new technological development and socioeconomic constraints and demands. For this reason, dynamic R&D programming is needed to revitalize the R&D programs at all 3 levels. The dynamic programming is described later.

The strategic model is developed as follows:

1. Based on the past and present trends and patterns of R&D in a particular area, the state of the art should indicate the status of R&D activities in a given mission or missions. Some of the parameters are R&D gaps, fragmentation, duplication, lack of positive direction, and general trend.
2. Based on this information and socioeconomic requirements and constraints, a general strategy of future R&D in each mission area can be developed. Future R&D strategy may indicate general thrust, orientation, problem areas, goals, priority, consequences, methodology, and interrelationships.
3. The general framework of R&D programs should be an optimal framework for carrying out future R&D programs indicated in 1 and 2.
4. This model will be useful to administrators, sponsors, and researchers in that it provides an overall picture and strategy of a given mission area and a basis for the decision-making process. Thus, basic R&D strategy for a given mission area may be established to serve as a guide for the development of tactical and action models. This model has a general applicability and utility regardless of geographic location or type of organization.

The second level of hierarchy is the tactical model, which is essentially an R&D planning and programming structure. This model is developed within the R&D strategy established in the strategic model and has the following characteristics: (a) establishes and defines positive objectives, study areas, and problem areas; (b) provides well-structured R&D programs for accomplishing objectives and goals established; (c) indicates various R&D flows, interrelationships, phases, and steps to accomplish the stated objectives; (d) serves as an R&D planning and programming tool that is concerned with the intermediate level of the decision-making processes; (e) is useful for R&D management control and for researchers; and (f) has a general applicability and utility regardless of geographic location or type of organization.

The third level of hierarchy is the action model. This defines the tasks indicated in the tactical model in relatively finite terms so that various R&D activities may be clearly programmed and spelled out and actual R&D may be performed based on this program model. This model (a) describes major tasks and projects that are necessary to place the research activities in clear focus; (b) indicates levels and scope of R&D activities of various tasks and projects and interrelationships among them; (c) serves as a test model for the hypotheses and directions established in both strategic and tactical models; (d) describes the R&D resource requirements necessary to reach certain objectives; (e) is useful for R&D management control and researchers; (f) may be developed or tailor-made as an R&D program for a particular institution depending on its policy, constraints, and resources; and (g) is the basis for actual performance (operation model) of R&D.

In summary, for any given mission area or a combination of mission areas, the first task is to establish the basic strategy with respect to the direction of R&D and to determine how the stated goals may be achieved. Then, within the framework of this R&D strategy, the tactical and action models will be developed to achieve the stated goals and objectives in terms of positive R&D programs and resource requirements. The strategic and tactical models have general utility independent of geographic location or type of organization, whereas the action model is a tailor-made program for a particular organization.

DEVELOPMENT OF CONCEPTS AND METHODS OF FORMULATING DYNAMIC R&D PROGRAMS

This phase entails the development and evaluation of possible alternative R&D programs with the eventual emergence of a final, dynamic program set.

Basically, there are 2 approaches in formulating an R&D program. One approach commonly used is based on the R&D needs. The other, which has not been utilized a great deal, is based on available or potential resources. Either approach may be used. Preferably the 2 approaches should be combined depending on a number of variables and constraints. This 2-way approach concept is shown in Figure 4.

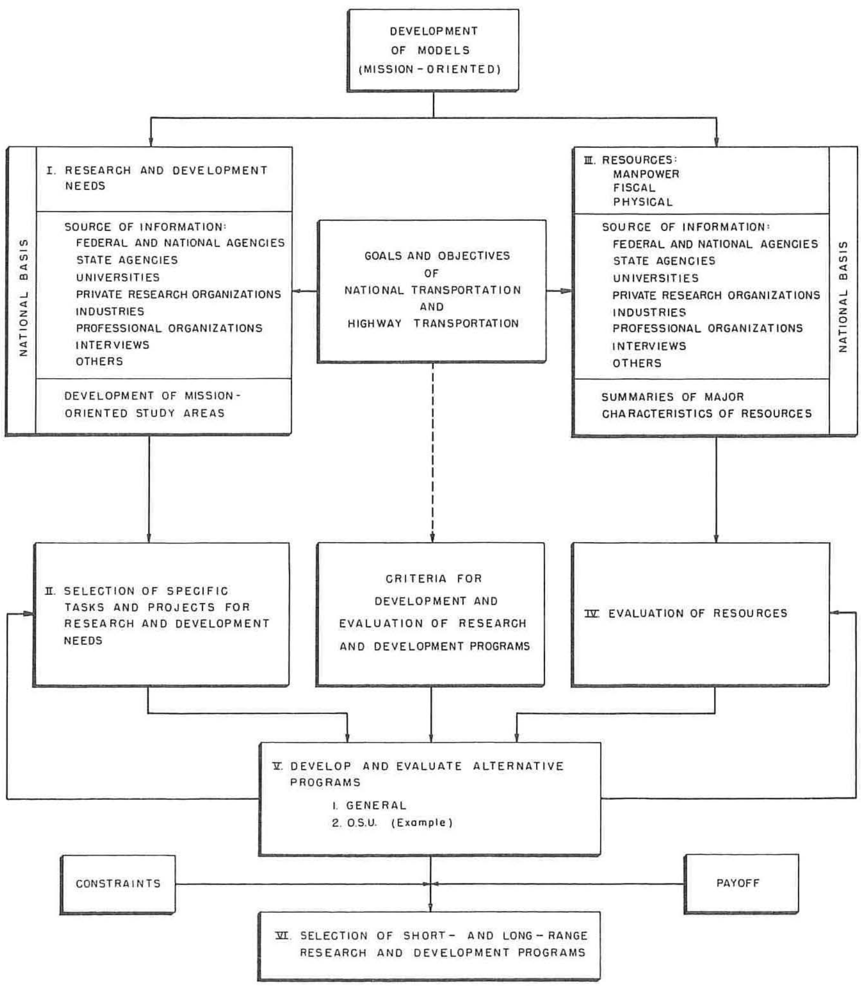

Figure 4. Development of model.

R&D Needs Approach

The first step in this approach is to determine the prevailing R&D needs. These needs are then categorized into 3 levels of R&D programs, namely, strategic, tactical, and action programs (or models), as described in the previous section.

Several studies related to research needs have been completed in recent years (1, 2, 3, 4). The state-of-the-art literature will be helpful in providing a good overview of R&D activities of the present and immediate past. This overview is essential in determining the general trend and pattern, gap fragmentation, duplication, and direction of R&D. It serves as a basis for formulating the strategic model, whose requirements and characteristics were described earlier. R&D needs studies are utilized for determining the future R&D needs. By studying programs, reports, and other socioeconomic requirements and constraints, future direction, thrust, goals, and priority of R&D are established as an integral part of the R&D strategy in each system element and mission area. Information from studies is supplemented by further information secured by interview and discussion with individuals involved in various research activities in highway transportation. Development of R&D strategy is mainly an administrative function.

Based on the R&D goals and priorities established in the strategic model (or program), R&D needs are then formulated into tactical and action programs. The tactical program, whose requirements and characteristics were explained earlier, involves developing well-structured R&D programs for a specific problem or study area. It indicates various R&D flows, interrelationships, phases, and steps to accomplish the stated objectives. General resource requirements (physical, manpower, and fiscal) may be established in this program. Development of the tactical program is an administrative-staff function.

Both strategic and tactical programs are not designed for special usage by any one organization. To the contrary, they have a general applicability and utility to most of the organizations across the country interested in highway transportation R&D.

The action program is then developed for the specific set of objectives within a problem area (or study area) as defined in the tactical program. This program involves judicious and logical selection and structuring of tasks and projects required for accomplishing the stated objectives. Various resource requirements (physical, manpower, and fiscal) necessary for achieving the stated objectives are also indicated in detail. Based on this action program, R&D can proceed. The action program is tailor-made to suit the particular policy, needs, capability, constraints, and resources available to a given organization. Development of the action program is mainly a staff function.

In summary, the R&D needs are first synthesized to form the basic R&D strategy along with other requirements for each system element or mission. Then, tactical and action programs are formulated of R&D strategy to solve specific problems.

Resources Approach

The conventional approach to R&D program development begins with R&D needs and formulates the program on the basis of need priorities within the limits of prevailing constraints. This approach assumes that all types of resources are equally available or that the necessary resources to accomplish certain missions can be planned and obtained. This is often not the case. In some areas of research and development, there exist unique resources (such as impact sleds, high-speed tracks, and specially trained research personnel) that possess very special R&D capabilities and capacities. If and when such unique resources exist, it is logical that a special effort should be made to formulate the R&D program to make the most efficient use possible of them within the confines of the national R&D thrust. This is the underlying principle of the resources approach to R&D program formulation.

Because this approach to program development is built around the special capabilities of specific resources, it is difficult to explain the procedure in general terms. For this reason, the procedure has been illustrated for a specific group of physical resources, namely, research laboratories. A similar procedure can be followed for

each of the other types of physical resources (such as field installations or tracks) or manpower resources. The resulting R&D program developed from such an approach will be fully feasible from a resource requirement standpoint and will provide full and efficient resource utilization.

An evaluation of the contribution of laboratories to the total capability of a research facility requires a knowledge of the different types of laboratories available and an understanding as to how these laboratories fit into the operation plan of such a facility. Figure 5 shows an overview of the interactions that take place between physical resources in the support of a set of research projects. The frequency and extent of these interactions are dependent on both the specific character of the research being pursued and the type of resources that are available.

Two general classes of laboratories can be readily identified, namely, primary laboratories and secondary laboratories. Primary laboratories are those directly involved in the performance of basic and applied research relating to highway transportation. Secondary laboratories are essentially support facilities involved along with the workshops in providing services to the primary laboratories and the field

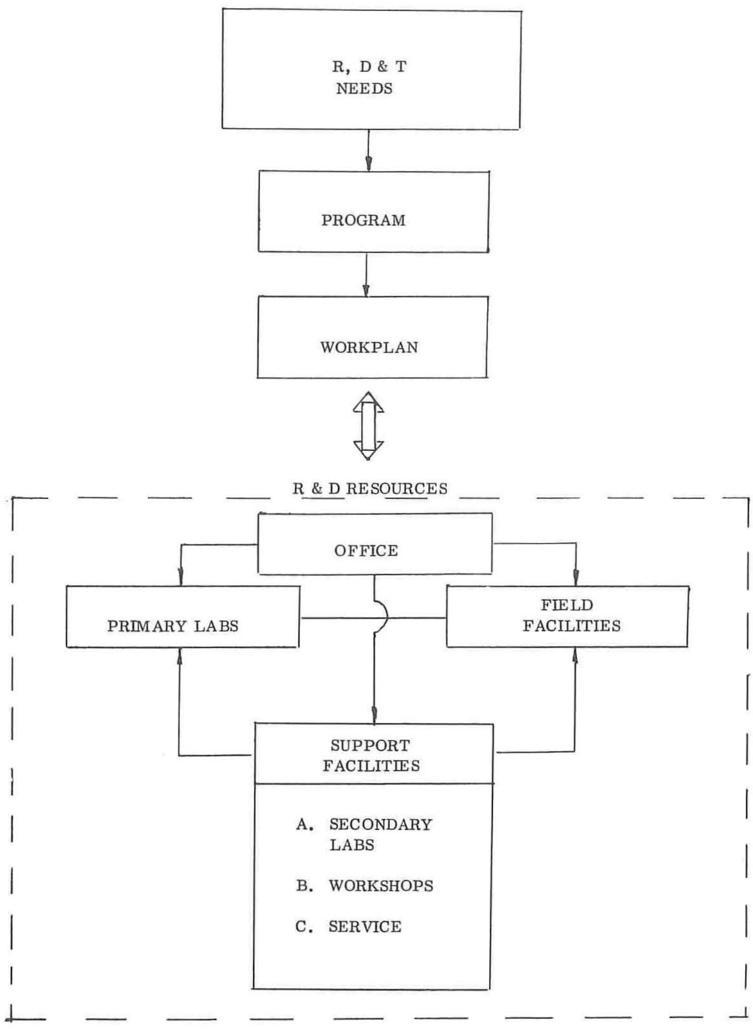

Figure 5. Study overview.

facilities. In general, these laboratories exhibit little or no trade-off with any other physical facilities. The primary laboratories by virtue of the direct highway orientation have the greatest effect on the overall capabilities of a research facility. For this reason they are critical in this approach to R&D program formulation.

Some of the different types of laboratories currently in operation in industry, at universities, and at research institutions in the primary class are highway materials; highway structures; optics and illumination; noise and vibration; corrosion and fatigue; environmental control; hydraulics; signs, markings, and control devices; vehicle guidance; vehicle dynamics and components; traffic dynamics and surveillance; system design and system operation; human behavior; medical analysis; impact; fuels and propulsion; accident reconstruction and analysis; simulation and simulator development; and pollution analysis and control.

Laboratories in the secondary class include communications, data processing and storage, photography, photogrammetry and photo interpretation, instrumentation, chemical, radiology, mechanical, electronics, electrical, and strength of materials.

Each physical resource has a specific capability for meeting different groups of research and development needs. The problem is to match the relevant needs with the appropriate resource. Once this match has been made it will be possible to formulate a set of R&D programs that will make efficient use of all available and potentially available resources.

Many factors combine to determine the research potential of a primary laboratory. Among these are the following: type and amount of specialized equipment available, quantity and quality of available manpower, efficiency of laboratory operation, flexibility of equipment allowing multipurpose usage; and capacity measure (volume of R&D that can be handled in laboratory).

Preliminary study has shown that the first 2 factors listed have the greatest effect on laboratory research potential. Hence, it becomes necessary to determine the major equipment commonly found in each of the primary laboratories. This will allow prevailing research needs (on a study area, project, or task level) to be related to the individual research capabilities of the laboratories with a greater degree of certainty. Once this has been done research programs based on research capabilities can be developed to make efficient use of all laboratory facilities as has been previously suggested. At the same time guidelines may be set for the acquisition of needed facilities in areas where no suitable facilities exist.

The selection of the proper physical resources for inclusion in a research facility is a difficult problem. This problem is complicated in the case of research laboratories because the research potential of such laboratories is a function of the availability of both equipment and manpower. The level of funding available further constrains the laboratory choice.

Figure 6 shows in flow-chart form a general model developed for use in making the laboratory selection. This model combines decision-making processes in 3 different levels of hierarchy: the strategic level, the tactical level, and the action level. The initial input to the model is a set of needs that have been selected from the universe of needs on the basis of similar resource requirements. Once a needs area has been selected for study it must undergo a policy review and a technical review to establish its validity. The purpose of the policy review is to determine whether the selected needs area (a) falls within the scope of interest of the parent research agency, (b) is in line with long-range policies and goals, and (c) offers sufficient potential payoff for inclusion in the R&D program. All needs areas that satisfy these 3 criteria are subjected to technical review. Needs that do not meet the criteria are dropped from consideration.

The purpose of the technical review is (a) to determine whether the selected needs area is still valid in view of present state of the art; (b) to determine whether the research in a selected area is within the technical capabilities of the parent research agency; and (c) to identify special problems involved in selected research that will require special attention and effort from the research staff. After the technical review, all research areas judged satisfactory can be included in the R&D program. Those judged unsatisfactory are dropped from consideration.

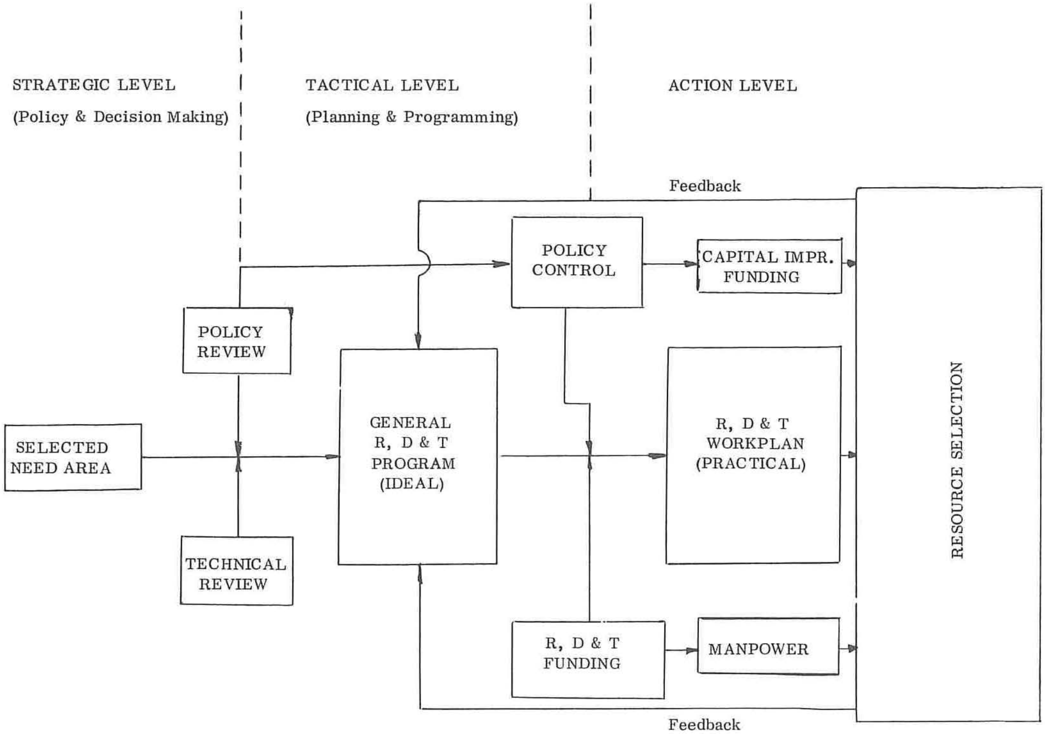

Figure 6. General model for resource selection.

The R&D program derived in this manner represents a compilation of study areas deemed worthwhile from both policy and technical standpoints. It is important to note that simply because a study area is on the program does not mean that it will be implemented in the short run. In order to be implemented, a study area must be moved from the program into the current work plan and defined more specifically in terms of a set of research projects. The impetus for such a move may come from any one of a number of causative factors, which have been termed "initial movers" because they supply the initial push. Prominent among these initial movers are the following: high national priority, promise of high reward, special interest by resident staff, available facilities, work shortages, and special policy decisions.

The exact nature of the initial mover of a particular project is important because it determines the extent to which physical facilities will be allocated to that project. For example, a project with a high national priority that promises high rewards may justify the allocation of large numbers of physical resources to bring about its swift completion, whereas a project generated because of special interests of individual researchers might be allocated lesser resources.

Once the initial impetus has been applied, a project must pass a second policy review, and sufficient funding must be found before it can be included in the work plan. The policy review at this level is primarily concerned with establishing priorities relating the project in question to other projects in the work plan. The priority assigned will determine the level of capital improvement funds that can be released to acquire needed physical resources among which are primary laboratories. The type of laboratory chosen depends on the detailed requirements of the selected project and the nature of other facilities already existing or planned. The concept of trade-off must also be considered. The size of the laboratory depends on the initial mover

concept, the quantity of manpower available, the amount of capital improvement funds available, and the size of other existing or planned facilities.

Once the selection has been made, pertinent information on research capability is fed back into the program development process, and the program is modified accordingly. In this manner the resulting R&D program is both dynamic and accomplishable.

In summary, an R&D program may be developed from either R&D needs or resources or from both. The initial concepts and methods are developed. They are to be refined during the course of further study.

Dynamic Programming of R&D

Once the R&D strategy and the tactical and action programs are formulated, R&D can be carried out and useful results obtained. However, any set of R&D programs so established may become partially or totally obsolete in time because of new technological development and varying socioeconomic requirements and constraints. For these reasons any R&D program set must go through a series of revitalization processes, more commonly known as a dynamic programming process. There are basically 3 types of R&D dynamic programming: internal, external, and internal-external.

The internal dynamic programming is applicable to an R&D area where R&D activities are relatively well defined in terms of objectives, activity elements, sequences, and feedback so that the R&D program may be formulated to possess inherent dynamic characteristics. Thus, under a given R&D strategy, the tactical (or tactical-action) program is formulated in terms of a series of R&D objectives, flows, and element interrelationships sequencing with a proper logic and feedback to have internal dynamic programming built in. Administrative control and monitoring, however, are still necessary.

The external dynamic programming, on the other hand, is more applicable to an R&D area where the R&D activities may not be readily defined or programmed with any reasonable certainty. Therefore, there must be some external mechanism that will make a given R&D program dynamic. The general concept and method of an external dynamic programming of R&D in highway transportation are shown in Figure 7. The basic concept is a periodic feedback and review of 3 programming models. It is recalled that the first task is to establish a sound R&D strategy. Then, within the framework of this strategy, tactical and action programs are developed. Thus, it is necessary to make a systematic reappraisal and review of the basic R&D strategy in the light of various dynamic requirements and constraints. For the purpose of this study, a 6-year review by administrative action is proposed. Detailed functions and

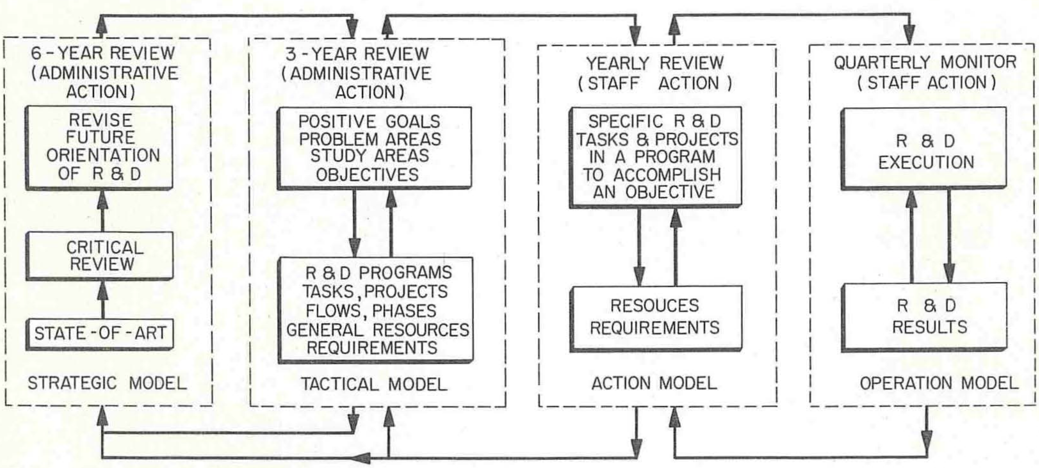

Figure 7. Dynamic programming of R&D in highway transportation.

activities are described in the diagrams. Then, within the framework of a revised R&D strategy, the tactical and action programs are reviewed and revised. The tactical program is revised every 3 years and the action program every year. The results of evaluation, reappraisal, and revision of these 2 programs are then fed into the strategic program to verify whether the strategy requirements and constraints are satisfied. Thus, an R&D program may be reoriented and revitalized to solve the stated problems.

The internal-external dynamic programming is a hybrid of the 2 previous methods. This method is useful for formulating a short-range R&D program by utilizing the internal dynamic programming method and for formulating a long-range R&D program by utilizing the external programming method when a large R&D program consists of both short- and long-range activities.

SUMMARY

In essence, this paper attempts to provide some guidance and direction to R&D program formulation. Emphasis is placed on the concepts and methods of formulating and developing R&D programs. The new concepts and methods are based on a mission-oriented systems approach. Based on this concept, various R&D program structure methods are developed. These concepts and methods provide a basis for better organized and systemized procedures and structures through which the entire effort of R&D in highway transportation may be guided, coordinated, and promoted toward positively defined goals.

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